Two-layer distributed optimal control for energy system integration

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Chapter 7

Conclusion and outlook

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We have studied how to embed dynamic agents that transform gas to power, or power to gas in the different energy grids, including: the gas grid, the mobility industrial grid, and the power grid, in a distributed and optimal manner. In this chapter, we discuss the main conclusions and findings presented in Chapters 3-6. We also provide suggestions for future research in this chapter.

7.1 Conclusion

This research is motivated and supported by a smart gas grid project (C9) of the Energy Delta Gas Research (EDGaR) consortium in the Netherlands. The project deals with investigating the capacity of smart grid technologies to facilitate the introduction of new gases into the distribution grids.

In particular, this research focuses on demand control of active energy consumers, supply control of renewable energy sources, and storage management system for the consumers and producers embedded in the multiple energy grids. In the following, we summarize the conclusions of each chapter.

In Chapter 3, we have considered supply coordination between energy grid operators and energy producers equipped with decentralized energy storage devices and energy converters. Specifically, the energy producers make decisions on their supply bids based on local information, yet still coordinate their bids to the grid operators in order to avoid overloading the grids, with the help of distribution charges. The setting results in a two-layer optimization problem experienced by energy producers and grid operators. Bidirectional communication between energy producers and grid operators is therefore examined in the chapter. We have formulated the associated optimal control problem in an MPC framework to anticipate the future conditions on the energy grids and changes on the supply profiles. We propose synchronous distributed algorithms, assuming that all energy producers and grid operators have a common clock to update their supply bids and distribution charges, respectively. It is confirmed from our numerical testings that a good initialization of distribution charges can reduce the number of iteration needed to converge to the optimal supply bids and distribution charges.

In Chapter 4, we have extended the approach given in Chapter 3 by implementing asynchronous exchange information on the proposed supply coordination algorithms. We prove the convergence of the asynchronous supply coordination algorithms in two cases. First, under some assumptions we prove the convergence of the asynchronous supply coordination algorithms in the static case, assuming that there are always sufficient sources to supply the amount of energy to the corresponding energy grids. Next, we prove the convergence of the asynchronous supply coordination algorithms by considering the dynamics of the energy producers from energy storage devices, when iteratively calculating the optimal supply bids and distribution charges. The proof is done under some additional assumption and an additional assumption on the time at which the algorithms reach the optimal solutions. The distributed asynchronous supply coordination is implemented and evaluated for a setup consisting of energy producers modeled in Chapter 3. It is numerically confirmed that the distribution charges increase from the initial values if the aggregated supply bids from the energy producers exceed the grid capacities. Otherwise, the distribution charges decrease with zero as a lower bound.

In Chapter 5, we have implemented the algorithms presented in Chapter 4 for biogas consumption and multi-energy supply coordination of prosumers. They build a central anaerobic digester for producing biogas from their organic waste. They are embedded in the low-pressure gas grid and in the low-voltage power grid. Here we proposed bidirectional communication between the prosumers and the digester operator and between the prosumers and the energy grid operators in order to obey the grid capacity constraints. It requires more iterations to converge to the optimal solutions when implementing the asynchronous exchange information than when implementing the synchronous exchange information.

In Chapter 6, we have not only coordinated the supply bids of prosumers to the associated energy grid operators asynchronously (as in Chapter 4), but also partly coordinated the states of the prosumers, i.e. imbalance between their local supply and demand, to their neighboring prosumers in a community asynchronously. Hence, the prosumers can contribute to minimize the community imbalance, while maximizing their profit by selling their surplus energy to the energy grids. We use a dynamic pricing mechanism, the so-called shadow price, for coordinating the imbalance in the community. The shadow prices help the prosumers to reach a consensus, i.e. through information topology presented in the A matrix, on how much they influence (help) each other. The number of iterations needed to converge to the optimal solutions depend on the initialization of shadow prices. In this chapter, we also considered the case when the prosumers have some flexible heat demand thereby allowing them to participate more actively in maintaining the balance in the community. To use similar steps as in Chapter 4 to prove the convergence of the corresponding asynchronous input and state coordination algorithms, it requires an additional assumption on the optimization problem, i.e., that all controllable inputs and states have quadratic functions in the optimization problem. It is numerically confirmed that with different initializations of the shadow prices, we converge to the same optimal values of shadow prices, but with different number of iterations. The shadow prices decrease from the initial values if the deviations between the expected and real influence from the neighboring prosumers are less than zero. Otherwise, they decrease till the deviations become zero.

7.2 Outlook

In this thesis, we have presented two-layer optimization problems. The low level consists of the individual optimization problem solved to maximize prosumers' profit, minimize all associated costs, minimize the imbalance within a community, and/or maintain the heat comfort levels of prosumers. The high level is due to the requisite in updating the distribution charges to ensure that the grid constraints are met. The integration of new stakeholders, including: aggregators of renewable energy producers and consumers and balancing responsible parties, into the setup considered in Chapter 3 may result in multi-hierarchical optimization problems. Examination of the integration is currently being studied under the Universal Smart Energy Framework (USEF). See [40] for detailed description about USEF.

Due to condition C1 in Chapter 4, the profit functions must be strictly concave, continuous, and twice differentiable. On the practical side, the revenue functions may not satisfy the condition, or may simply be a linear function. Hence, considering the convergence of the asynchronous supply coordination with this practical consideration is a topic that deserves future investigation.

In fact, heat can be effectively stored for a long period. However, as the heat buffer has a maximum capacity, some surplus heat is wasted under the setting we propose in Chapter 5. It is therefore of interest for future work to embed the prosumers in some heating network in order to use the waste heat of the μ-CHPs.

An experimental implementation of the proposed asynchronous distributed coordination algorithm may bring new insights which deserve some attention and further investigation. Additionally, inclusion of practical control considerations due to on-off constraints of the energy converters is among future extensions for Chapter 6. This results in considering non-convex constraints when iteratively and asynchronously solving the prosumers' optimal control problem.

Another future avenue for Chapter 6 is to extend the problem by incorporating flexible power demand due to, e.g., the use of plug-in electric vehicles. By coordinating the switch-on time of the plug-in electric vehicles, the prosumers can participate in demand response more actively.

Regarding the four restrictions $R_1 - R_4$ in Subsection 6.2.1, we still have some freedom in designing the static information topology shown in A matrix. As seen in the simulation results in Subsection 6.5.2, different A matrices result in diverse total community imbalance levels. It is therefore of interest as well to investigate an approach to find the optimal information topology.

As stated earlier, good initialization of distribution charges and shadow prices reduces the number of iterations needed to converge to the optimal solutions. Hence, future research may include a method to optimize the initial values of distribution charges and shadow prices hence reducing the number of iterations during the bidding process between the prosumers and the energy grid operators and between the prosumers and their neighboring prosumers in the community, respectively.